



Influence of urbanization-driven land use/cover change on climate: The case of Addis Ababa, Ethiopia

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ARTICLE INFO

Keywords:

Land use change
Urban scale climate
Urban heat island (UHI)
Normalized differencing vegetation index (NDVI)
Climate change

ABSTRACT

Land use change is the second most important anthropogenic influence on climate beside the emission of greenhouse gases. Urbanization is leading to significant land use changes in Africa since the continent is undergoing rapid urbanization and population growth in recent decades. Addis Ababa is one of these fast growing cities in the continent. Therefore, detection of land use change is very important to identify its impact on climate and sustainable land use management of the city. The study used Landsat images to generate land use/land cover change map for the city. The normalized difference vegetation index (NDVI) is used to detect the major changes of vegetation cover occurred between 1986 and 2011 as a result of land use and land cover change. Downscaled HadCM3 simulations under A2 and B2 emission scenarios is used to investigate future urban heat island (UHI) over the city of Addis Ababa. In the city, the analysis of Landsat images has shown that the built-up areas have increased by 121.88 km² within the last 25 years. This finding is consistent with NDVI images taken over the same period that reveal a decline in vegetation cover. The impact of the urbanization-driven land use/cover change has resulted in notable nocturnal urban heat island (UHI) as revealed from an average increase in minimum temperature of 1.5°C at the centre of the city relative to rural site over the 1960–2001 period. The mean of the 2006–2010 spatial minimum temperature anomaly with respect to the base period mean of 1981–2005 is consistent with the observed UHI. The temperature in the central areas (both commercial and residential sectors) of Addis Ababa is warmer than the surrounding areas. The thermal gradient increase from about 1.44°C at the centre (Arada, Addis Ketema, Lideta and Kirkos) to 0.21°C at the peripheral parts of the city (Gulele, Bole, Nefasilk-Lafto, Kolfe Keranio and east of Yeka sub-cities) transecting across the hot (high-density urban) to moderately warm to cool (non-built-up) areas. However, the maximum temperature and rainfall exhibit variability that follows topographic differences. Future urban climate change projections of urban heat island formation under A2 and B2 emission scenarios show that the nocturnal UHI will be intense in winter or dry season episodes in the city. The highest urban warming is from October to December (2.5°C to 3.2°C) during 2050s and 2080s.

1. Introduction

Urbanization transforms naturally covered land into impervious land cover (Xian et al., 2008). Urban land cover can have significant effects on local climate and environment (Wu and Murray, 2003; Zhou et al., 2004; Grimmond, 2006; Carter et al., 2015). Understanding urban landscape conversions and interactions between natural phenomenon and human activities is important for proper land and climate change management (Mantyka-pringle et al., 2012). Several studies have indicated that urban centers are warmer than their surrounding countryside leading to an increased urban heat island (UHI) (Babazadeh

and Kumar, 2015; Mohan et al., 2012). The UHI is an anthropogenic phenomenon resulting from the distinct surface modification caused by human settlement in urban areas. In urban built-up areas, the use of air conditioners and transportation systems bring additional heat source into the urban layer (Wilby and Perry, 2006). In contrast to the countryside, building materials and non-vegetated surface covers retain more solar energy during the day, and have lower rates of radiant cooling during the night time (Santamouris, 2013). When a considerable portion of the natural land cover is changed by surface built-up, it traps or absorbs incoming solar radiation during the day time and then re-radiates it at night due to a decrease in albedo (Babazadeh and

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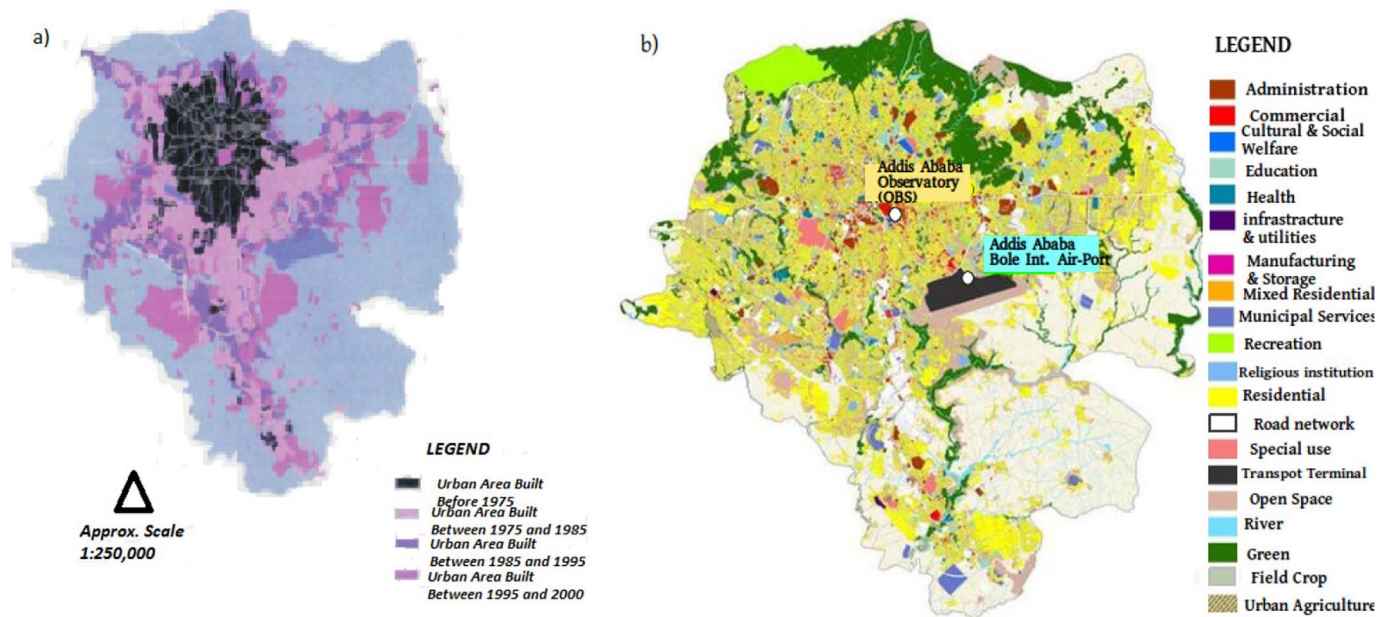


Fig. 1. Addis Ababa city a) physical expansion; and b) existing LULC and the locations of the two meteorological stations (Source: Office of the Revision Addis Ababa Master Plan (ORAAMP, 2002)).

Kumar, 2015). The reduction of evaporation and evapotranspiration due to impermeable surfaces and reduced vegetation are other factors that lead to UHI. The heat generated from local infrastructure and heat trapped by urban air pollution could also play some role in aggravating the UHI effect (Oke, 1997). In urbanized areas the cooling process is made slower by keeping night-time air temperatures high (Mohan et al., 2012; Olaide et al., 2013) through condensation and inertial heat release which compensate for the radiative heat loss in contrast to surrounding rural areas. Therefore, the UHI has the strongest signal at night and in the winter months.

The UHI intensity is also found to be affected by meteorological conditions. For example, the UHI intensity is observed to decrease due to increased wind speed and high cloud coverage (Grimmond, 2006; Joseph and S, 2013) while UHI is intensified in the presence of high pressure or anticyclone system or during dry summer season (Kuttler et al., 2007; Morris and Plummer, 2001). Moreover, increases in population density of a city increases UHI intensity.

Given the scale of urbanization coupled to the dearth of available studies on Africa in general and the absence of serious efforts to understand the impact of urbanization induced land use/land cover change on climate change, this study aims to assess land use changes and their impact on urban scale climate through their UHI effects. Addis Ababa, capital city of Ethiopia, is chosen for this case study because of notable spatial expansion, population growth and many developmental activities such as rapid expansion of infrastructure (e.g., massive construction of roads, railway, buildings). This expansion is partly driven by the pressure from hosting numerous international and sub-regional and continental organizations including the United Nations Economic Commission for Africa (UNECA), the African Union (AU), the World Bank, the European Commission, and United Nations Development Program (UNDP). As a result, immense change in land cover and land use over Addis Ababa has occurred during the last decades. As noted in many cities in other part of the world (Toy and Yilmaz, 2010; Kotharkar and Surawar, 2015), this urban growth in population and industry converts the landscape from natural to more and more impervious urban land leading to major changes in natural environment and climate. The impact of land use and land cover change is highly felt through marked temperature contrast between the centre and outskirts of a city, which is a manifestation of UHI. Moreover, the increase in land utilization and modification of land use and land cover over time

modify the micro-climate of a city. Therefore it is important to study existing and future occurrences of UHIs in Addis Ababa city where rapid socioeconomic development and spatial transformation are taking place.

The structure of the paper is as follows: Section 2 describes study area and its historical growth trend and the existing land use. Section 3 describes the data and methods employed. Section 4 presents the assessments made on land use and land cover changes using Landsat images. The assessment involves estimation of annual percentage changes in land use and land cover. This section also discusses the relation between physical expansion and population growth. The observed urban climate change and future Heat Island effects based on observational data and statistically downscaled HadCM3 model simulations under A2 and B2 emission scenarios are also presented in Section 4. Finally, conclusions are drawn in Section 5.

2. Study area

Addis Ababa city, the capital city of Ethiopia since 1889 with approximate centre located at 9°N , 38.7°E , is situated in the central highlands of the country and covers an area of approximately 526 km^2 with a population of 2.9 million (CSA, 2011) according to population projections made for 2011. A study by the Office for the Revision of the Addis Ababa City Master Plan (ORAAMP, 2002) shows that, the historical growth of the built-up areas of the city could be divided into five distinct periods (1887–1936, 1937–1975, 1976–1985, 1986–1995, and 1996–2000). The first period is the early development period that took place from 1887 to 1936 and is known for its haphazard and extended settlements of military camps and the occupation of large compound by landlords as villages. The extended area was between Gulale (in the East) and Yeka (in the West) and Entoto (in the North) and Bekulo-Bet (in the South). During this period, the total built up area was 18.63 km^2 . Assuming constant growth in each year, the average growth of the built up area was 0.37 km^2 per annum (Abdissa, 2005). During the period between 1976 and 1985, the built-up area had increased by 47.88 km^2 , thus increasing the cumulative total to 108.38 km^2 . Similarly between 1986 and 1995, the built-up area had expanded by 29.25 km^2 , increasing the cumulative total to 137.63 km^2 (Fig. 1a, see also Table 1). Simultaneously, horizontal expansion took place in all directions of the city, where both legal and squatter settlements were established. It was

Table 1
Expansion of Built-up areas of the city of Addis Ababa (Source: Office of the Revision Addis Ababa Master Plan (ORAAMP, 2002)).

Period	Built up areas (km ²)
Before 1975	60.50
1976–1985	108.38
1986–1995	137.63
1996–2000	146.73

Table 2
Land use/cover classes used in this study.

Classes	Definition
Urban/built up areas	Residential, industrial and commercial complexes, transportation and road networks, communication and utilities
Water	All areas of streams and reservoirs
Bare land	Areas of thin soil, sand, or rock, almost without vegetation
Agriculture and Tree Vegetation	Trees, grass land, shrubs, crop fields and cultivated lands
Forest Land	Deciduous, evergreen and mixed forests (natural and man-made forests)

estimated that, out of the total of 94,135 housing units built in the city between 1986 and 1995, 15.7% (14,794 housing units) were built by squatters (Melesse, 2005). The physical expansion of the city between 1996 and 2000 led to increases in the built-up area of Addis Ababa by 9.09 km², reaching a cumulative total of 146.73 km² (Melesse, 2005).

Fig. 1b shows the map (scale of 1:150,000) of urban LULC for the study area. The two meteorological stations representing urban and sub-urban sites are also indicated in the map. The dominant LULC features are residential with mixed-use (which accounts for an area of 153.1 km²), green and open space (which accounts for an area of 236.9 km²), road net-work and transport terminal (which accounts for an area of 57.6 km²), rivers (which accounts for an area of 10.9 km²), manufacturing and storages (which accounts for an area of 17.2 km²). The green space are mainly located in the mountainous areas and along river banks (Fig. 1b). Manufacturing and storage functions dominate the southern part of the city, Akaki Kaliti sub city, whereas mixed-use is dominant in the central parts of the city, and open areas as well as farmlands occur around Bole Airport area (Fig. 1b).

Table 3
Summary of area statistics of Landsat image classification for 1986, 1999 and 2011.

Land cover classes	1986	1999	2011
	Area (km ² (%))	Area (km ² (%))	Area (km ² (%))
Forest	225 (43)	166(32)	55(11)
Urban built up	87(17)	114(22)	209(40)
Agriculture and Vegetation	167(32)	171(33)	141(27)
Bare land	40(8)	68(13)	114(22)
Total	519(100)	519(100)	519(100)

Table 4
Rate of change of land use and land cover in Addis Ababa (km²/year).

Land cover classes	1986–1999	1999–2011	1986–2011
Forest	– 4.55	– 9.25	– 6.81
Urban built-up	2.05	7.93	4.88
Agriculture and Vegetation	0.36	– 2.53	– 1.03
Bare land	2.13	3.85	2.96

Table 5
NDVI values of January 2011 before and after Atmospheric Correction.

Land cover classes	NDVI without correction	NDVI with correction
Forest	0.28	0.39
Urban built-up	– 0.33	– 0.24
Agriculture and Vegetation	– 0.15	– 0.05
Bare land	– 0.25	– 0.15

3. Data and methodology

3.1. Data

To assess land use/land cover (LULC) changes, three Landsat images taken on clear cloud-free days were selected. Accordingly, images from Landsat-5 Thematic Mapper (TM) sensors taken on December 23, 1986; January 25, 1999 and January 10, 2011 were analyzed. All Landsat TM images were obtained from U.S. Geological Survey (USGS) Centre for Earth Resources Observation and Science (EROS). The images are geo-referenced using the Universal Transverse Mercator (UTM) map projection (Zone 37) based on WGS 84 reference ellipsoid. The Landsat TM grid cell size is 30 m by 30 m pixel. Data on population size of the sub-cities in Addis Ababa by area and density is also used to understand the

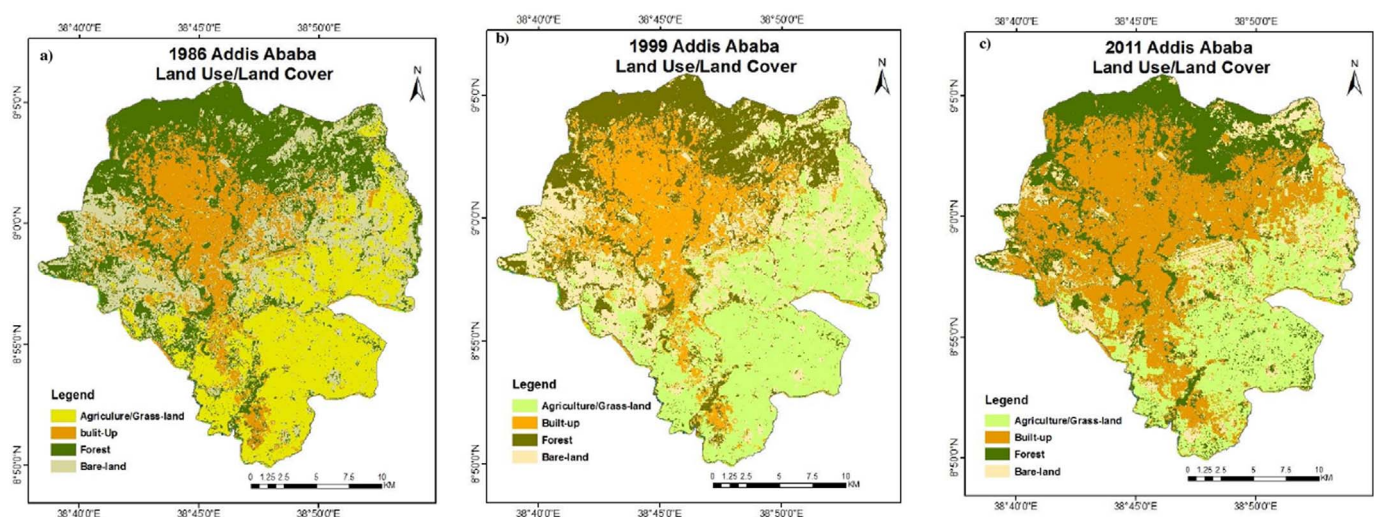


Fig. 2. Addis Ababa LULC in a) 1986, b) 1999 and c) 2011.

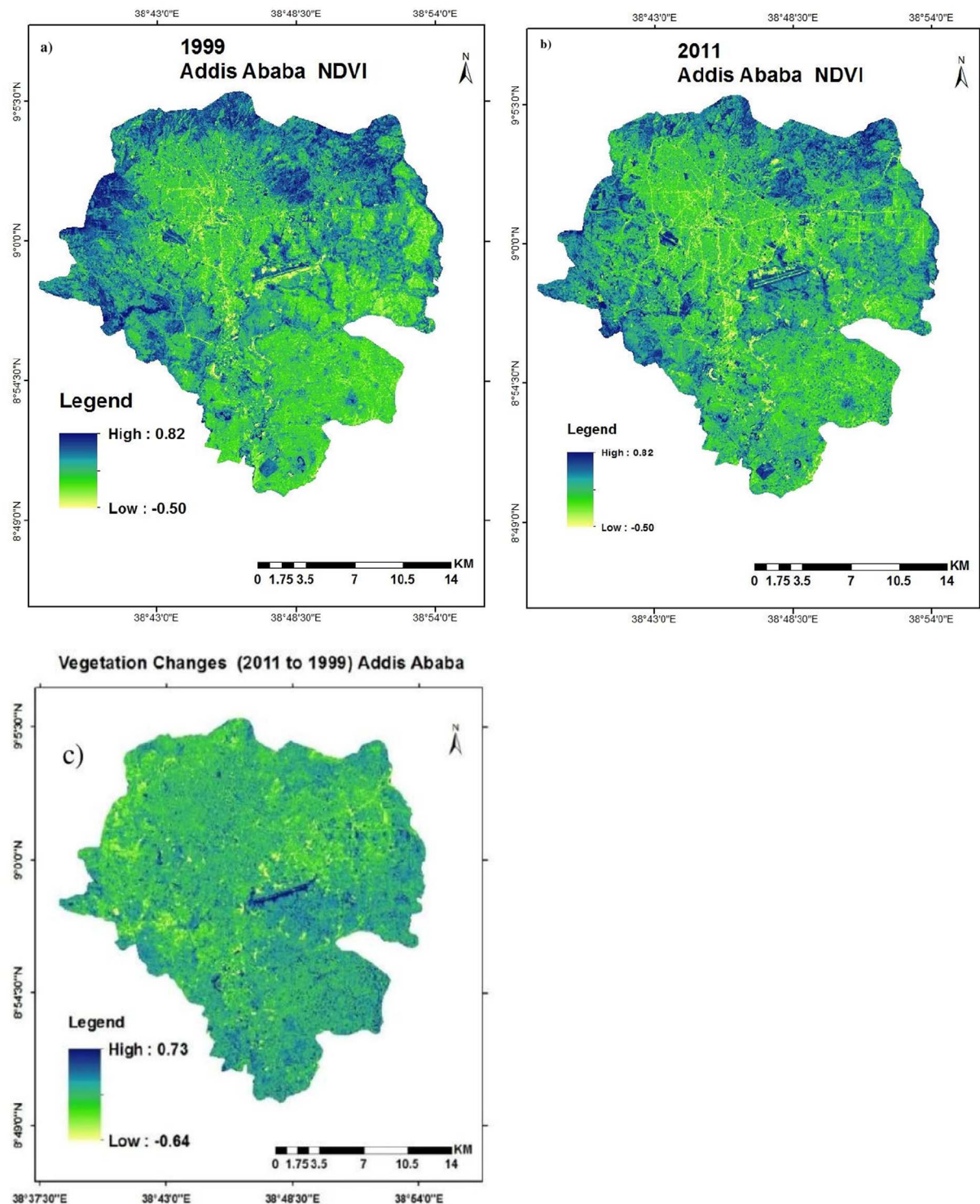


Fig. 3. NDVI images for addis ababa for (a) January, 1999 and (b) January 2011. Note: Bare Land: <0.5 and dense vegetation: >0.75 (Source: (Vermote et al., 2002)).

underlying causes of LULC changes.

Rainfall, minimum and maximum temperature data at a spatial resolution of 10 km by 10 km over Addis Ababa and its surrounding for a period of 20 years covering the 1981–2010 period are obtained from the National Meteorological Agency (NMA) of Ethiopia. These data are used to assess the climate of the city. In addition, minimum temperature from the period from 1961 to 2001 at the two stations (Addis Ababa observatory (OBS), an urban site, and Bole International Airport (BOL),

a rural site) are obtained from NMA for analysis of observed UHI of Addis Ababa city. Assessment of the future UHI during the period 1960–2099 is based on downscaled data from HadCM3 Global Circulation Model (GCM) under A2 and B2 emission scenarios. These two emission pathways, A2 and B2, are chosen since A2 represents a diverse world with increasing global population and economic growth that is disjointed and slow (IPCC, 2000); whilst B2 represents a scenario under which population grows on a continuous basis, accompanied by

Table 6
Population size of the 10 sub-cities in Addis Ababa by area and density.

Sub-city	Population (Number)	Area (km ²)	Population Density (Number/km ²)
Akaki Kaliti	197,180	118.08	1669.9
Nefas Silk Lafto	344,043	68.30	5037.2
Kolfe Keranyo	466,539	61.25	7617.0
Gullele	291,113	30.18	9645.9
Lideta	219,418	9.18	23,901.7
Kirkos	240,651	14.62	16,460.4
Arada	230,065	9.91	23,215.4
Addis Ketema	277,786	7.41	37,488
Yeka	377,091	85.98	4385.8
Bole	336,115	122.08	2753.2
Addis Ababa	2,980,001	526.99	5654.8

intermediate level of economic development.

3.2. Methodologies

3.2.1. Land use change

Land cover change in general and land use change in particular would have either direct or indirect impacts on the extent and conditions of changes that occur on the land surface as a whole. The changes could be transformation of land cover to land use or vice versa. The rate of LULC change, R (km/year) as given by

$$R = \frac{A_t - A_{t-p}}{p} \quad (1)$$

is used in this study, where A_t is recent area of LULC (i.e., LULC at time t) in km², A_{t-p} is previous area of LULC (i.e., LULC at earlier time $t - p$) in km² and p is the interval between recent and previous period in years.

3.2.2. Land use classification

There are two land use classification methods, namely supervised classification and unsupervised classification techniques. In supervised classification process, spectral signatures are developed from a priori identified locations in the image. These specified locations are given the generic name (e.g., 'forest') and are defined by the user. In general a vector layer is digitized over the raster scene. This vector layer will consist of different polygons overlaying on different land use types (Jensen, 2004). The unsupervised classification techniques, on the other hand, do not require the user to identify any information about

the features enclosed in the images; the user simply identifies which bands of Landsat TM image should be used to create the classifications, and determine the number of classes to categorize the land cover features. The unsupervised classification of land use in this study was based on Anderson scheme. The scheme identifies residential land, water bodies, agricultural land, bare land and forest land (Anderson et al., 1976). Once the image in each year was classified, change detection algorithm was used to determine changes in land cover for three periods: 1986–1999, 1999–2011 and 1986–2011. This approach was also followed by Jensen (2004) to monitor LULC changes in Atlanta, Georgia.

However, with this technique, some identified land use may be different from actual observed land use. In particularly, differentiating bare-land, some built-up of brown roof top and agriculture land are difficult. The performance of unsupervised classification needs to be verified using Google-Earth map. Therefore, in this study unsupervised image classification was employed and its accuracy is verified using Google-Earth map with the recent image (in this study, image for 2011). ENVI 4.2 and Arc-Map10.2 software were employed for image classification. The final outputs were maps (at scale of 1: 150,000) of LULC changes. The land use/cover classes used in the study is given in Table 2.

3.2.3. Analysis of vegetation change

General assessment of land cover change could be also assessed using the normalized differencing vegetation index (NDVI) values. NDVI implicitly shows the overall change in vegetation cover of a given place. NDVI is, therefore, used to complement the above analysis of LULC changes. Vegetation cover protects climate change by reducing the temperature of urban areas (Makhlouf, 2009). Hence monitoring of vegetation cover is vital despite requiring synoptic and representative coverage of satellite imagery (Birkneh, 2007). In doing the assessment of LULC changes, NDVI is used as the most ordinary ratio indices of vegetation. The NDVI is empirical formula intended to stress the spectral difference between the red and near infrared regions of electromagnetic spectrum. The closer NDVI is to one the more the vegetation is active photo-synthetically (Jensen, 2004). NDVI is evaluated as

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (2)$$

where NIR is near infrared band for a given pixel, RED is the red band response.

Atmospheric correction is needed when NDVI is used for such

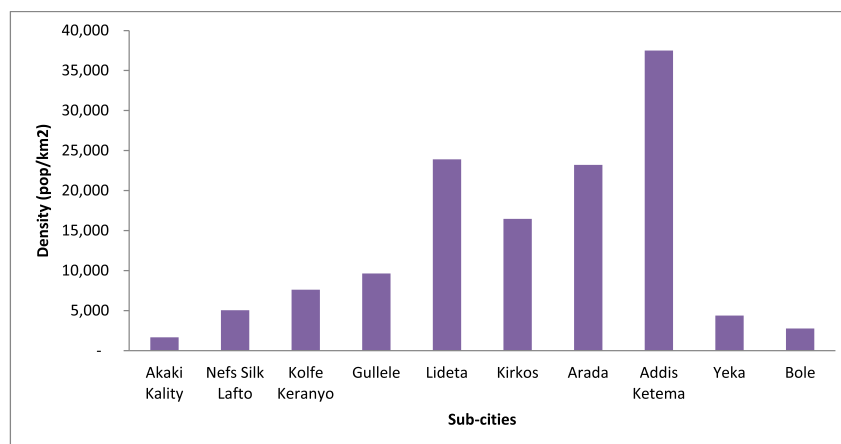


Figure 4: Population Density of Addis Ababa sub-cities.

Fig. 4. Population Density of Addis Ababa sub-cities.

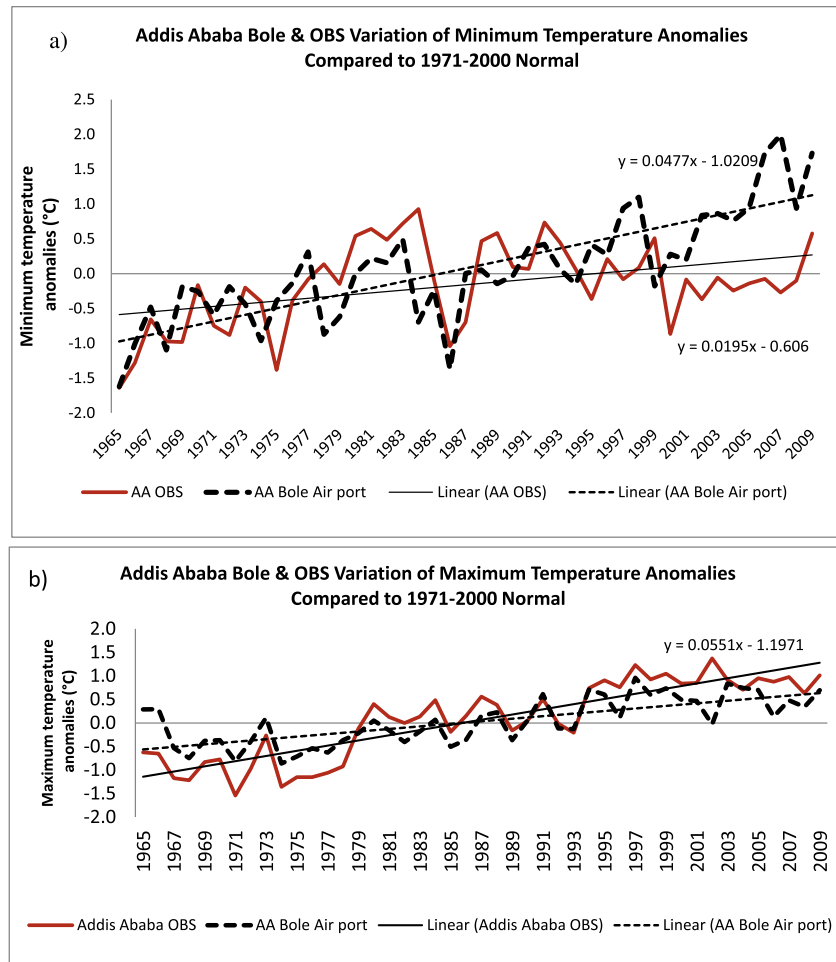


Fig. 5. The anomalies of (a) minimum and (b) maximum temperature at BOL and OBS stations compared to 1971–2000 base period mean.

purposes since atmospheric effects, which are a result of molecular scattering and absorption, can affect the quality of NDVI extracted from remote sensing measurements. Specifically, atmosphere is a major source of noise for accurate measurement of surface reflectance with optical remote sensing (Song and Woodcock, 2003; Honkavaara et al., 2009; Hadjimitsis et al., 2010; Bagheri, 2011). Though, errors caused by atmospheric effects vary with the spectral channel used (Che and Price, 1992), a mean difference of 18% for the NDVI was recorded before and after the application of darkest pixel method to Landsat TM/ETM + images (Hadjimitsis et al., 2010). Therefore, the NDVI is adjusted taking into account the influence of atmosphere on reflectance measurements.

After the above atmospheric correction is made for two NDVI images taken on January 25, 1999 and January 10, 2011, vegetation cover change was estimated using Arc-GIS from difference of the two NDVI images. While difference in the dates of observations in 1999 and 2011 may introduce some error because of subseasonal scale variability in NDVI in principle, the fact that the observations were both taken in January which is dry winter period over the area implies impact of such difference between the two observation years is insignificant in reality. Therefore the changes in vegetation cover from 1999 to 2011 due to LULC can easily be detected from the NDVI images.

3.2.4. Observed and predicted urban heat island (UHI)

One of the major problems in the investigation of observed and future UHI is the absence of a dense and long-term station network in the city. For this reason, data from only two stations (OBS and BOL) covering the period 1960–2001 were analyzed.

3.2.4.1. Observed UHI. Minimum temperature data from OBS and BOL synoptic stations are used for UHI assessment. The population density of Bole sub-city is about 2753 and the corresponding density at OBS station area is about 23,900 inhabitants per square kilometer. OBS serves as the urban reference station in the calculation of UHI, whilst BOL station serves as rural station. Addis Ababa UHI is then defined as

$$UHI = T_{minOBS} - T_{minBOL} \quad (3)$$

where T_{minOBS} and T_{minBOL} are the daily minimum temperature at OBS and BOL stations, respectively.

3.2.4.2. Downscaling of future UHI. Wilby (2008) used SDSM to downscale and predict future UHI for the city of London. The same method was applied for predicting UHI for Addis Ababa. A statistical relationship between change in minimum temperature and climate variables from reanalysis was developed for downscaling nocturnal UHI. The predictand is daily minimum temperature difference between the Addis Ababa Bole rural site and that of Addis Ababa observatory urban site. The predictors of large scale indices were obtained from the reanalysis of data from the National Centre for Environmental Prediction (NCEP).

The linear regression, which was determined to be robust in previous work (Wilby et al., 2002), is used in this study. The predictand UHI intensity is regressed against the meteorological variables X :

$$UHI = aX + b \quad (4)$$

The p-value, determined from T-test of the regression coefficients between predictand and predictor, is used as a measure of statistical significance of the relationship.

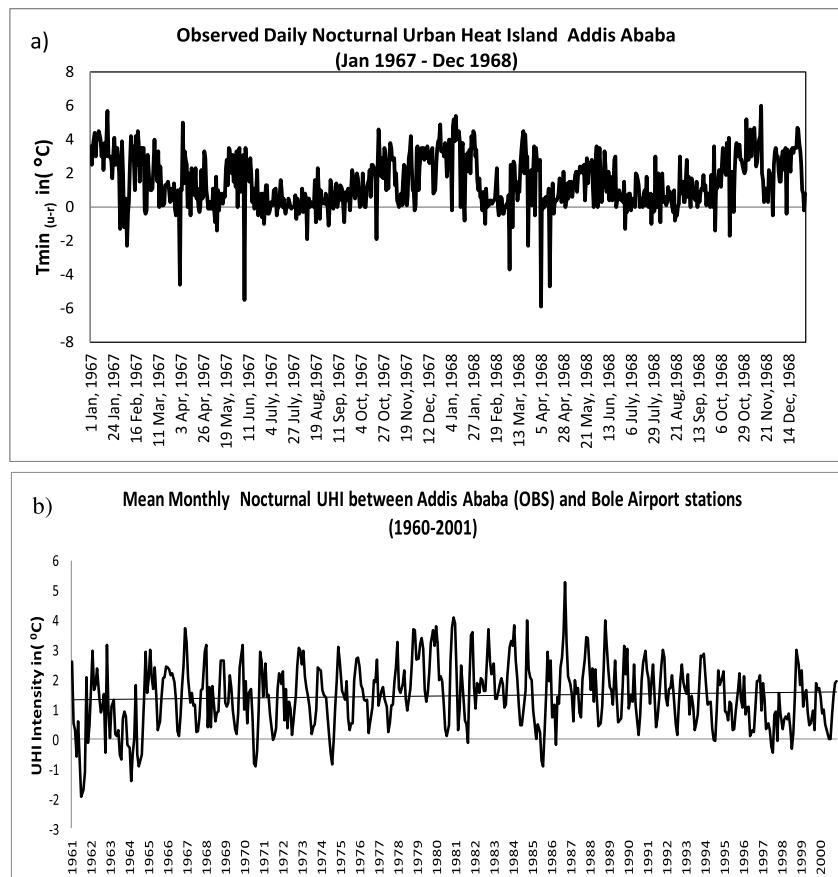


Fig. 6. (a) Mean daily nocturnal UHI intensity for the coldest period (January 1967 to December 1968); (b) Mean monthly nocturnal UHI for the period (1960–2001). UHI is the difference of minimum temperature at OBS and BOL stations.

The SDSM model was calibrated using the difference of daily minimum temperatures (Bole and OBS stations) from 1961 to 2000; and the reanalysis of the National Centre for Environmental Prediction (NCEP) climate variables centered on the nearest grid location in the study area (Latitude: 9.01N and Longitude: 38.74E) are used to downscale UHI as per Eqn. (4). The predictors of large scale indices are obtained from the outputs of HadCM3 model runs based on A2 and B2 scenarios.

4. Results and discussion

4.1. Land use change

Fig. 2 shows the LULC classification in terms of agriculture and grass land, built-up, forest and bare-land for the three Landsat images taken in 1986, 1999 and 2011. In 1986, the city's land use and land cover were dominated by forest cover in the northern and northwestern parts of the city while agricultural and grasslands dominated the southern and southeastern sectors. The built-up area was concentrated in the central part of the city (Fig. 2a). The land use and land cover maps of the 1999 (Fig. 2b) and 2011 (Fig. 2c) show an expansion of built-up areas leading to the shrinkage of the forest and agricultural lands in all parts of the city.

The LULC changes that occurred during the period under consideration is summarized in Table 3. Water body was not detected in the analysis of land use, however, trees were observed in the map along the line of dry-river in the city. About 43%, 31.9% and 10.5% of the total area were under forest cover in 1986, 1999 and 2011, respectively. The bare land covers were about 7.7%, 13.04% and 21.9% of the total geographical area of the city in 1986, 1999 and 2011, respectively.

About 32%, 33% and 27% of the areas were agricultural/vegetation land in 1986, 1999 and 2011, respectively. About 16.9%, 21.9% and 40% areas were under built-up in 1986, 1999 and 2011, respectively. These figures show that there has been a steady increase in urban built-up areas in contrast to almost proportional decrease in forest over the city. Moreover, there is also substantial increase in bare land in contrast to a decrease in agriculture and vegetation cover. In general, the analysis of the satellite images have shown that the built-up areas have increased by 121.88 km² within the 25-years period.

The rate of change for forest lands was negative, which implies a decline in areal coverage, whereas settlements and degraded land increased their areal extent at the expense of the forest and agricultural lands. Over the study period, the extent of built-up areas has increased by 4.88 km² per annum (Table 4) against 76% decrease of forest cover and 15% decrease of agricultural/vegetation land areas (Table 3). Even though grass and trees showed a certain growth trend, bare-land has increased mainly because of large-scale extraction of construction materials. The above figure on expansion per annum is based constant growth rate which does not reflect variability from year to year.

Table 4 shows the amount of land in km² per annum converted to or gained from other categories of land use based on a constant land cover change within the period. For instance, 1.03 km² per annum of agricultural and tree cover land, and 6.81 km² per annum of forest lands of the 1986 were transformed to built-up land. In other words, built-up cover in 2011 is a result of shift of 4.88 km² per annum of exhausted land since 1986.

4.2. Vegetation cover change

Table 5 shows that the NDVI of the original image tends to show

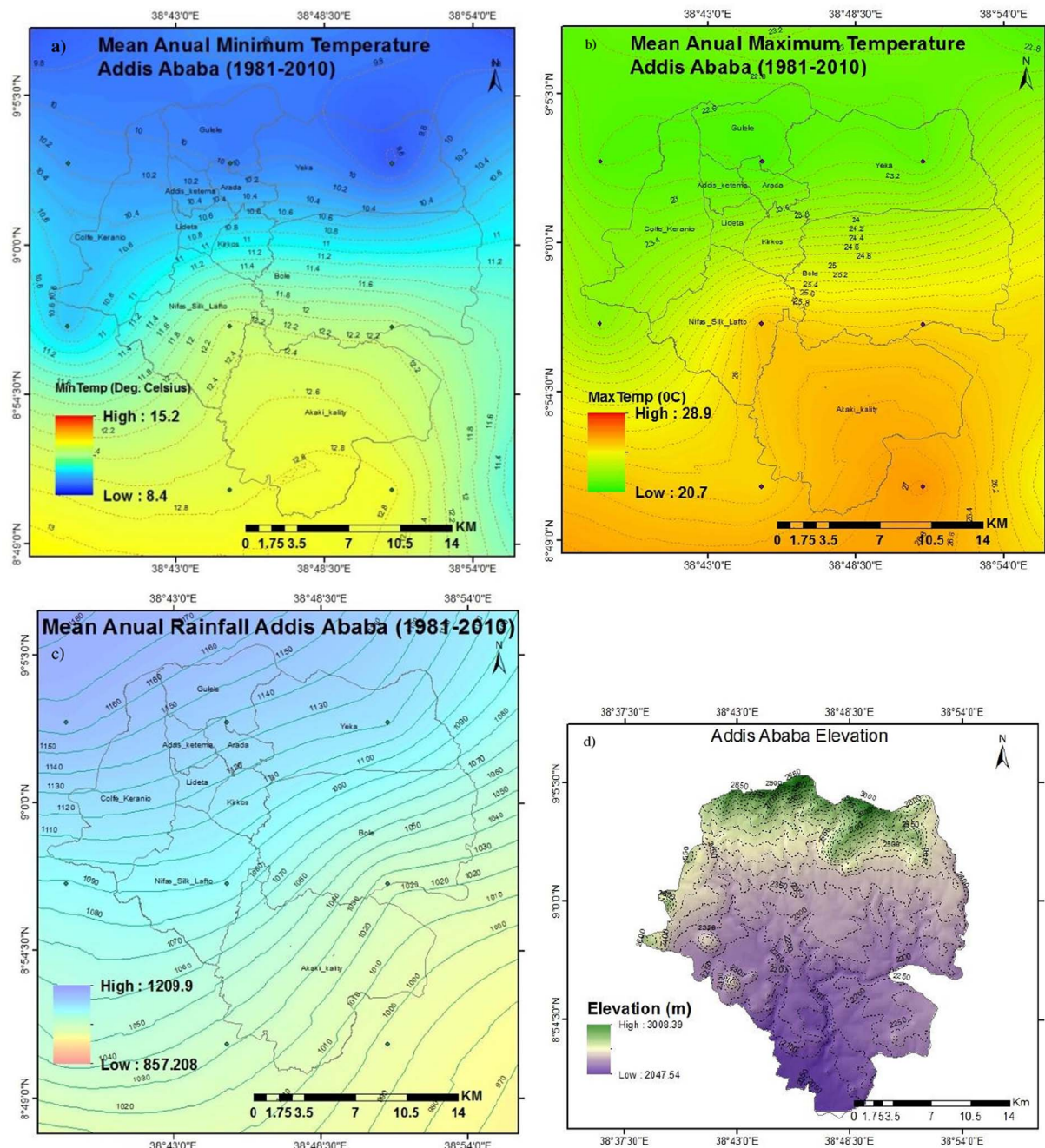


Fig. 7. a) Long term (i.e., over the 1981–2010 period) mean annual minimum temperature; b) Mean annual maximum temperature; c) Mean annual total rainfall; and d) Elevation map of Addis Ababa city.

poor vegetation conditions as a result of contribution from surface reflectance towards the RED part of the spectral signature in Eqn. (2). Thus, eliminating the negative effects of gaseous absorption, molecular and aerosols scattering improve the quality of the image. This is consistent with results reported by Vermote et al. (2002) who identified that the NDVI values, on average, increased from -0.33 to 0.38 after atmospheric correction.

The NDVI conditions in 2009 and 2011 are shown in Fig. 3a–b on the same colorbar scale that show shifts of color towards lower NDVI from 1999 to 2011 clearly indicating vegetation degradation. The NDVI pixel maximum, for instance, decreased from 0.82 in 1999 to 0.66 in 2011 whereas NDVI pixel minimum decreased from -0.50 in 1999 to -0.29 in 2011 indicating the overall range of NDVI changes. Spatially, the major change in vegetation cover occurred in the central and

eastern parts of Addis Ababa (Fig. 3c).

4.3. Population distribution in Addis Ababa

The demographic, social and policy issues are among the major causes for LULC changes of a given area (Carlson and Arthur, 2000). Addis Ababa population had exhibited significant increase over the last century. The city has been undergoing rapid rate of urbanization triggered by rural-urban migration and socio-economic development. The city's population had tripled between 1961 and 1984 and almost doubled between 1984 and 2008. Such an increment in population requires additional space for settlement and construction of auxiliary services and infrastructure. In 2000 the population was 2,112,737, and is projected to be 2,980,001 by 2011. The average population density of the

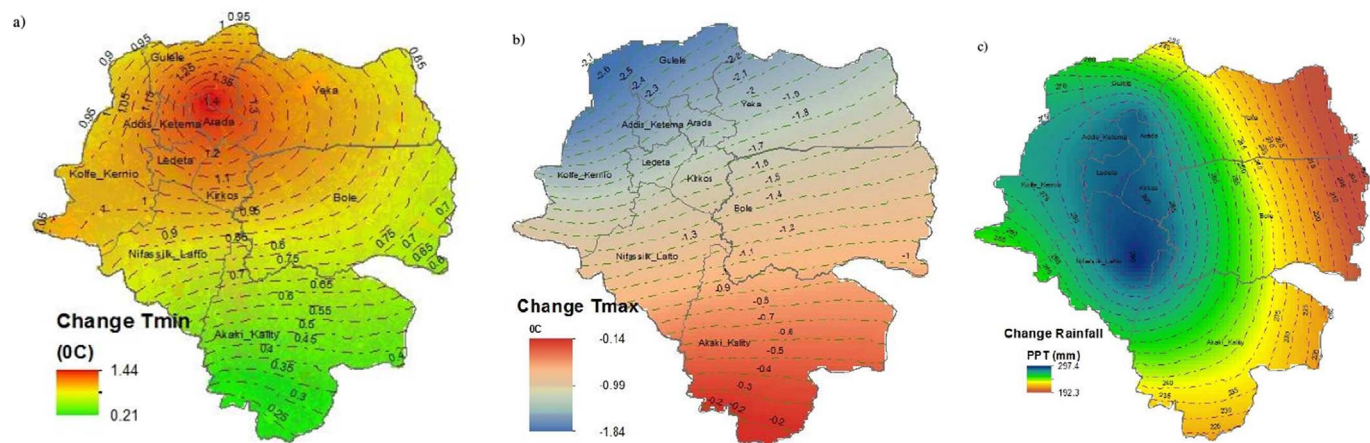


Fig. 8. Average (2006–2010) changes in (a) minimum, (b) maximum temperatures and (c) rainfall with respect to the base period (1981–2005) annual mean.

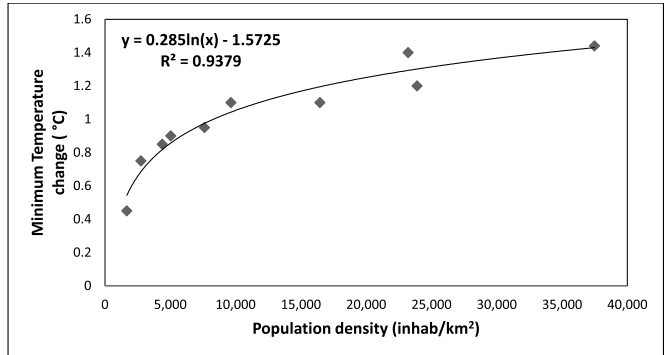


Fig. 9. The variation of average (2006–2010) minimum temperature change of Addis Ababa (with respect to the base period (1981–2005) mean) with population density at ten sub-cities. Note that the average minimum temperature change was found from grid values at the ten sub-cities.

Table 7
The large scale atmospheric predictors and their relation to UHI (predictand).

Predictand	Atmospheric predictor (X)	p-value
UHI	Mean sea level pressure	0.0000
	500 hpa airflow strength	0.0012
	500 hPa geopotential height	0.0000
	850 hPa airflow strength	0.0001
	850 hPa meridional velocity	0.0013

city is about 5654 persons/km², which shows an increase of 1624 person/km² between 2000 and 2011 (CSA, 2011).

The population distribution in the city shows that the highest percentage, 15.7% or 466,539 of the city's population, live in Kolfe Keranyo sub-city (western sector), occupying an area of 61.25 km². This is followed by Yeka sub-city (eastern side) that accounts for 12.7% or 377,091 of the city's population and occupying an area of 85.98 km². The third largest sub city is Nefas silk Lafto (southwestern sector) with 11.5% or 344,043 of the city's residents living in an area of 68.30 km² (Table 6). Population density of sub-cities is indicated in Fig. 4. The density of population shows that the central parts of the city including Addis-Ketema, Arada, Kirkos and Lideta sub-cities have very high densities (16,000–23,900 persons/km²) as compared to that of Bole, Yeka, Nifas-silklafto and Akaki sub-cities (1669.9–5037.2 person/km²) (see Table 6 and Fig. 4).

4.4. Observed climate of Addis Ababa city

The maximum and minimum temperature anomalies recorded at

OBS and BOL from 1965 to 2009 with respect to the 1971–2000 base-period mean have been fitted with a linear line to estimate the observed linear trends during this period (Fig. 5). Statistically significant warming trend in the minimum temperatures at both OBS and BOL stations are detected in the observation during the period from 1965 to 1983. However, the warming in the inner parts of the city (i.e., at OBS station) is significantly higher than that at the rural station (i.e., BOL station) for both minimum and maximum temperatures (Table 6). The increase in the maximum temperature is higher than that of the minimum temperature, and the trends in minimum temperature change at BOL and OBS stations are 0.19 °C and 0.47 °C per decade, respectively (Fig. 5a). The warming trends in maximum temperature (Fig. 5b) for BOL and OBS stations are 0.55 °C and 0.27 °C per decade, respectively.

The daily nocturnal urban heat island (UHI) for the selected coldest period of 1967–1968 showed that the warmest days in the city centre (at OBS) was in November (warmer by about 6.0 °C than BOL site) whereas the coldest day was in April (colder by about −5.8 °C than BOL site) (Fig. 6a). The urban warming is enhanced during the dry season from October to January and is weakened during the wet season from June to September (Fig. 6b).

The spatial pattern of mean annual minimum and maximum temperature for the period 1981–2010, shows decrease from northern highlands of Gulele and Yeka sub-cities to Akaki-Kality sub-city (Fig. 7a–b). The average minimum temperature of the city was between 10.3 °C to 12.8 °C, whilst the average maximum temperature was between 23.4 °C to 28.6°. The spatial distribution of rainfall shows that Gulele sub-city in the north is the wettest (i.e. about 1160 mm), whereas Akaki-kality sub-city is the driest of all sub-cities with mean rainfall of about 1010 mm (Fig. 7c). The three climate variables seem to follow largely the elevation pattern in Fig. 7d. Patterns with high peaks enjoy cold and wet conditions whereas low lying areas experience warm and relatively dry conditions.

The change in the mean annual minimum and maximum temperatures as well as rainfall during 2006–2010 is evaluated with respect to the mean of the base period of 1981–2005. The minimum temperature and rainfall patterns apparently follow that of land use change (see Fig. 8a,c and Fig. 2) that result from urbanization and the topography of the city, while maximum temperature changes relate only to topography (Fig. 8b). The minimum temperature or nocturnal temperature shows that the warmest or hot spot area is to be found in commercial and mixed residential areas at the city centre (Fig. 8a). It is to be noted that the hot spot areas in Fig. 8a cover the most populated and commercial areas such as Arada, Addis Ketema, and Lideta subcities (see Table 6). This is consistent with the understanding that an urban make up which is characterized by construction of residential buildings and roads with dark surfaces creates strong UHI effects (Shishegar, 2013). The

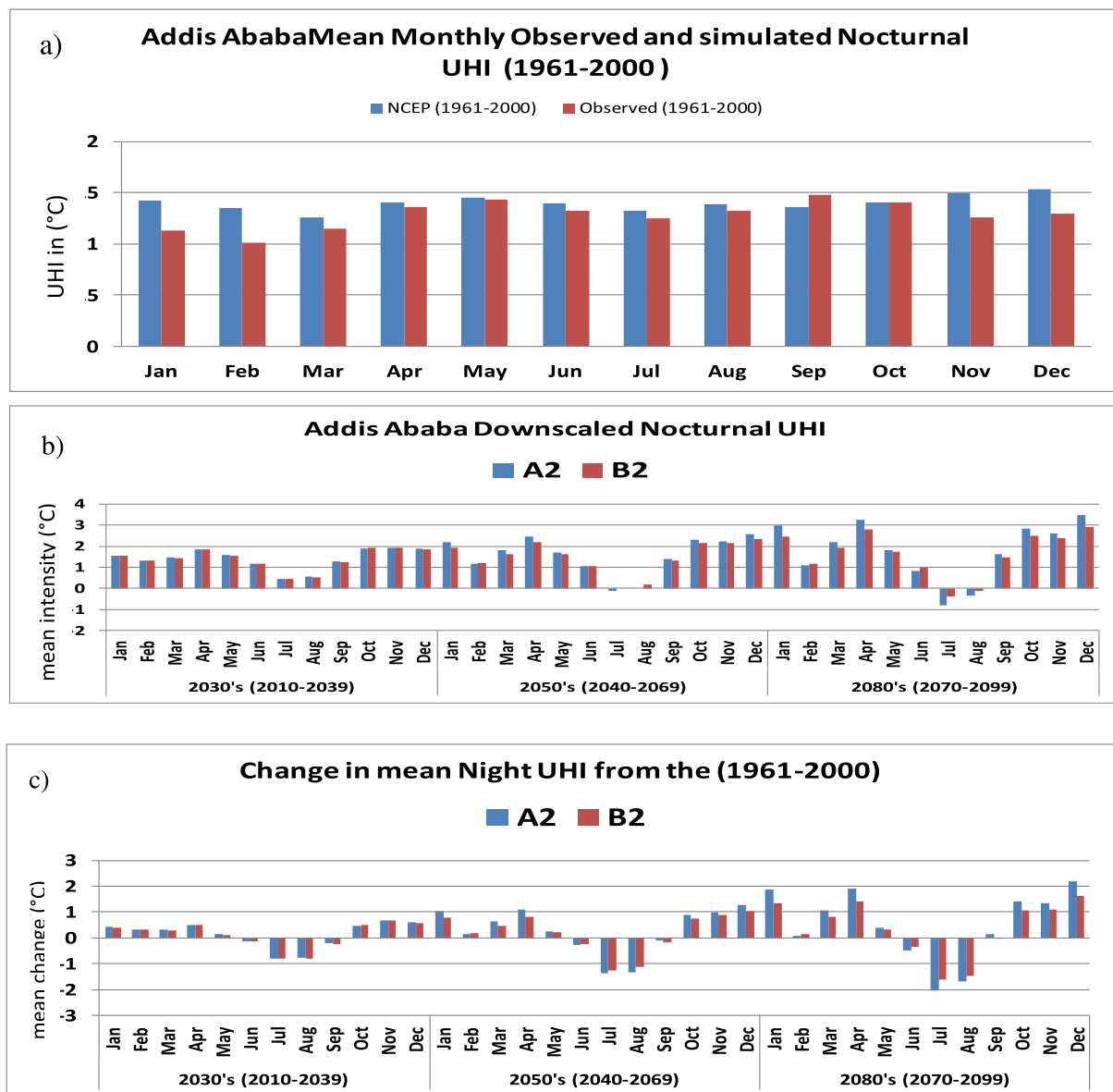


Fig. 10. Monthly mean (a) observed and reanalysis nocturnal UHI, (b) downscaled UHI under A2 and B2 for the 2030s, 2050s and 2080s, and (c) change in UHI with respect to base period 1961–2000.

temperatures in the central parts of Addis Ababa are at their extreme in the commercial and residential areas. The hot spots of thermal gradient range from 1.44 °C in the central part of the city (Arada, Addis Ketema, Lideta and Kirkos) to 0.21 °C at the edge of the city (Gulele, Bole, Nefasilk-Lafto, Kolfe Keranio sub-cities and east of Yeka sub-city) where there is relatively cooler, sparsely populated and green areas. The maximum temperature does not follow the urban land use pattern. The maximum temperature during 2006–2010 rather follows the topography with the coldest in the North and relatively mild cold in the South with respect to the base period mean. The highest decrease in the northern uplands of the city reaches up to -2.7 °C (Fig. 8b). The rainfall gradient is also high in the residential and commercial areas by about 290 mm per annum (Fig. 8c).

Fig. 9 shows the relation between minimum temperature change and population density at ten sub-cities. The minimum temperature change has strong correlation with change in population density of the ten sub-cities since higher population density requires higher building density and, therefore, results in enhanced radiation trapping and high thermal inertia (Steenneveld et al., 2011). The correlation is nonlinear which arises partly from proximity to rural or urban centre. In the

former case, ventilation from rural areas may smooth out the sharp temperature gradient. The finding that shows change in temperature has strong correlation with population density confirms earlier understanding (Oke, 1982). Therefore, the agreement also gives credence to the gridded observational data.

4.5. Projected changes in nocturnal UHI under emission scenarios A2 and B2

The study identified major predictor and predictand relationships from linear regression. The predictor and predictand relationships for the observed data were used to downscale ensembles of the same local stations variables for the future UHI climate driven under the A2 and B2 emission scenarios for the period 1961 to 2099 as described in Section 3.2.4.2. The predictors of large scale indices are obtained from the outputs of the HadCM3 model under A2 and B2 scenarios.

To develop a statistical model five variables, as shown in Table 7, were screened. The analysis shows that the mean sea level pressure, 500 hPa airflow strength, 500 hPa geopotential height, 850 hPa airflow strength and 850 hPa meridional velocity strongly influence UHI. The

pressure is related to cloud cover, and, high cloud cover with low pressure system reduces UHI (Morris and Plummer, 2001; Schlunzen et al., 2010). The variables exhibit high and statistically significant correlation, with p-values less than 0.005. Fig. 10a shows comparison of mean climatology of nocturnal UHI between observed and NCEP re-analysis for the 1961–2000 base period. The observation and NCEP UHIs exhibit very good agreement with minor differences during winter months of November to February (see Fig. 10a).

Changes in nocturnal UHI show an increase in nighttime temperature during the dry seasons of October to January in all projected periods (2030s, 2050s and 2080s), whereas, during June to September, the rural site is warmer than the inner city (See Fig. 10b). The highest urban warming is expected to occur from October to December (2.5 °C and 3.2 °C) in the 2050s and 2080s respectively. Interestingly, weakening of the mean UHI intensity occurs in summer (the Kiremt or the long rainy season). Both A2 and B2 emission scenarios suggest occurrence of more intense UHI events from October to December. This follows the patterns revealed in the observed UHI. These changes are expected to be more persistent and intense during drought periods.

5. Conclusions

The study examined temporal changes in LULC over Addis Ababa city using Landsat images taken in 1986, 1999 and 2011. The study also investigated the urbanization-driven climate change, specifically nocturnal temperature change. The results indicated that built-up areas increased sharply over the 25 years since 1986 while forest areas, vegetation covers and agricultural lands exhibited a sharp decline. As a result, the extent of bare lands had increased, mainly in the southern and eastern parts between forest areas and agricultural fields, especially in mountain and quarry areas.

The observed changes in LULC were largely attributed to urbanization. Changes in land use were accompanied by changes in local climate of Arada, Addis Ketema and Kirkos sub-cities, which exhibited increases in the minimum temperature of up to 1.45 °C. The hot spot temperature was clearly identified between the densely built-up, and the surrounding sparsely built-up and green areas within the administrative boundaries of the city.

The investigation made on the projected nocturnal UHI of Addis Ababa shows that, the UHI will be intense in winter (dry season). By the 2050s and 2080s the change in mean nocturnal temperatures from October to December could be 2.5 °C and 3.2 °C, respectively. This suggests the need for urban greening by creating urban city parks and urban trees. The dry season has the highest frequency of hot conditions at both sites of the city (OBS and BOL), while the wet season recorded the lowest frequencies of hot condition. This indicates that the influence of urbanization on the climate is much stronger during the dry season than wet season. This has its own implications for thermal comfort planning and decision-making in the city. High temperatures observed in the city centre suggest a heat stress and potential health risk. Hence measures that are capable of mitigating impacts of the increasing temperatures associated with the UHI are required in order to improve the city climate.

Acknowledgments

The first author wishes to acknowledge and offer gratitude to the Ethiopian Civil Service University and the Open Society Foundation of Civil Society, for financial support during the doctoral study at UNISA and scholarship award 2014 for research visit to the climate modeling group at the University of Nebraska, Lincoln USA respectively. The corresponding author (GMT) acknowledges the Humboldt Foundation for the financial support through the Humboldt fellowship during which this work was initiated. The authors would also like to extend their heart-felt gratitude to the National Meteorological Agency (NMA) of Ethiopia for providing valuable data for the research. As well as the

U.S. Geological Survey (USGS) Centre for Earth Resources Observation and Science (EROS) for providing the Landsat images utilized in the study.

References

- Abdissa, F., 2005. Urban Expansion and the Livelihoods of the Peri-Urban Agricultural Community. MSc Thesis. Addis Ababa University, Addis Ababa, Ethiopia.
- Anderson, J.R., Hardy, E., Roach, J.T., Witmer, R.E., 1976. A land use and land cover classification system for use with remote sensor. In: USGS 964 Report. USGS, pp. 28.
- Babazadeh, M., Kumar, P., 2015. Estimation of the urban heat island in local climate change and vulnerability assessment for air quality in Delhi. *Eur. Sci. J.* 55–65. ISSN:1857-7881.
- Bagheri, S., 2011. Nearshore water quality estimation using atmospherically corrected aviris data. *Rem. Sens.* 3, 257–269.
- Birkneh, T., 2007. Assessment of Land Degradation Using Gis Based Model and Remote Sensing in Bishan Guracha-adilo Sub-catchments, Southern Ethiopia. MSc Thesis. Addis Ababa University, Addis Ababa, Ethiopia.
- Carlson, T., Arthur, S.T., 2000. The impact of land use-land cover changes due to urbanization on surface microclimate and hydrology: a satellite perspective. *Journal of Global and Planetary Change* 25 (1–2), 49–65.
- Carter, J., Cavan, G., Connelly, A., Guy, S., Handley, J., Kazmierczak, A., 2015. Climate change and the city: building capacity for urban adaptation. *Prog. Plann.* 95, 1–66. <http://dx.doi.org/10.1016/j.progress.2013.08.001>.
- Che, N., Price, J.C., 1992. Survey of radiometric calibration results and methods for visible and near infrared channels of noaa-7, -9, and -11 avhrrs. *Remote Sens. Environ.* 41, 19–27.
- CSA, 2011. Demographic Survey for the City of Addis Ababa. Central Statistics Agency of Ethiopia (CSA), Addis Ababa, Ethiopia.
- Grimmond, C.S.B., 2006. Progress in measuring and observing the urban atmosphere. *Theor. Appl. Climatol.* 84, 3–22.
- Hadjimitsis, D., Papadavid, G., Agapiou, A., Themistocleous, K., Hadjimitsis, M.G., Retalis, A., Michaelides, S., Chrysoulakis, N., Toullos, L., Clayton, C., 2010. Atmospheric correction for satellite remotely sensed data intended for agricultural applications: impact on vegetation indices. *Nat. Hazards Earth Syst. Sci.* 10, 89–95.
- Honkavaara, E., Arbiol, R., Markelin, L., Martinez, L., Cramer, M., Bovet, S., Chandelier, L., Ilves, R., Klonus, R., Marshal, P., Schlpfer, D., Tabor, M., Thom, C., Veje, N., 2009. Digital airborne photogrammetry? a new tool for quantitative remote sensing? a state-of-the-art review on radiometric aspects of digital photogrammetric images. *Rem. Sens.* 1, 577–605.
- IPCC, 2000. A Special Report on Emission Scenarios: a Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Jensen, R., 2004. *Introductory Digital Image Processing: a Remote Sensing Perspective*. Prentice Hall.
- Joseph, H., S. F., 2013. *Environmental Fluid Dynamics, Chapter 11: Urban Heat Island*. CRC Press/Taylor & Francis Group.
- Kotharkar, R., Surawar, M., 2015. Land use, land cover, and population density impact on the formation of canopy urban heat islands through traverse survey in the nagpur urban area, India. *J. Urban Plann. Dev.* [http://dx.doi.org/10.1061/\(ASCE\)UP.1943-5444.0000277](http://dx.doi.org/10.1061/(ASCE)UP.1943-5444.0000277), 04015003.
- Kuttler, W., Weber, S., Schonnefeld, J., Hesselschwerdt, A., 2007. Urban/rural atmospheric water vapour pressure differences and urban moisture excess in krefeld, Germany. *Int. J. Climatol.* 27. <http://dx.doi.org/10.1002/joc.1558>.
- Makhelouf, A., 2009. The effect of green spaces on urban climate and pollution. *Journal of Health. Sci. Eng* 6, 35–40.
- Mantyka-pringle, C.S., Martin, T.G., Rhodes, J.R., 2012. Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis. *Global Change Biol.* 18. <http://dx.doi.org/10.1111/j.1365-2486.2011.02593.x>.
- Melesse, M., 2005. City expansion, squatter settlements and policy implications in addis ababa: the case of kolfe keranio sub-city working papers on population and land use change in central Ethiopia. *Acta Geograph.* 2.
- Mohan, M., Kikegawa, Y., Gurjar, B.R., Bhati, S., Kandya, A., Ogawa, K., 2012. Urban heat island assessment for a tropical urban airshed in India. *Journal of Atmospheric and Climate Sciences* 2, 127–138.
- Morris, C.I.S., Plummer, N., 2001. Quantification of the influences of wind and cloud on the nocturnal urban heat island of a large city. *J. Appl. Meteorol.* 40, 169–182.
- Oke, T.R., 1982. The energetic basis of the urban heat island. *Q. J. R. Meteorol. Soc.* 108, 1–24. <http://dx.doi.org/10.1002/qj.49710845502>.
- Oke, T.R., 1997. Urban climates and global environmental change. In: Thompson, R.D., Perry, A.H. (Eds.), *Applied Climatology: Principles and Practice*. Routledge, London, pp. 273–287.
- Olaide, A.M., Kayode, S.E., Edris, I., 2013. An assessment of urban heat island in akure using geospatial techniques. *Journal of Environmental Science. Toxicology And Food Technology* 6, 24–34.
- ORAAMP, 2002. Addis Ababa in Action: Progress through Partnership, Strategic Planning for Addis Ababa: Executive Summary. UN-Habitat, Cities Alliance. Addis Ababa City Government, Addis Ababa.
- Santamouris, M., 2013. Using cool pavements as a mitigation strategy to fight urban heat island: a review of the actual developments. *Journal of Renewable and Sustainable Energy Reviews* 26, 224–240. <http://dx.doi.org/10.1016/j.rser.2013.05.047>.
- Schlunzen, K.H., Hoffmann, P., Rosenhagen, G., Riecke, W., 2010. Long term changes and regional differences in temperature and precipitation in the metropolitan area of hamburg. *Int. J. Climatol.* 30, 1121–1136.

- Shishegar, N., 2013. The impact of green areas on mitigating urban heat island effect. *Int. J. Environ. Sustain.* 9 (1), 119–130.
- Song, C., Woodcock, E.C., 2003. Monitoring forest succession with multitemporal landsat images: factors of uncertainty. *Geosci. Remote Sens.* 41, 2557–2567.
- Steeneveld, G.J., Koopmans, S., Heusinkveld, B.G., Hove, L.W.A.V., Holtslag, A.A.M., 2011. Quantifying urban heat island effects and human comfort for cities of variable size and urban morphology in The Netherlands. *J. Geophys. Res.* 116, D20129. <http://dx.doi.org/10.1029/2011JD015988>.
- Toy, S., Yilmaz, S., 2010. Evaluation of 10-year temperature differences between urban and rural areas of a well-planned, unindustrialized, and medium-sized Turkish town, erzincan. *J. Urban Plann. Dev.* 349–356.
- Vermote, F., Saleous, Z., Justice, O., 2002. Atmospheric correction of modis data in the visible to middle infrared: the moderate resolution imaging spectroradiometer (modis): a new generation of land surface monitoring. *Journal of Remote Sensing of Environment* 83 (1–2), 97–111.
- Wilby, R., Perry, G., 2006. Climate change, biodiversity and the urban environment: a critical review based on london, UK. *Prog. Phys. Geogr.* 30, 73–98.
- Wilby, R.L., 2008. Constructing climate change scenarios of urban heat island intensity and air quality. *Environment and Planning B-Planning & Design* 35, 902–919.
- Wilby, R.L., Dawson, C.W., Barrow, E.M., 2002. Sdsm- a decision support tool for the assessment of regional climate change impacts. *Journal of Environmental Modelling and Software* 17 (2), 145–157. [http://dx.doi.org/10.1016/S1364-8152\(01\)00060-3](http://dx.doi.org/10.1016/S1364-8152(01)00060-3).
- Wu, C., Murray, A.T., 2003. Estimating impervious surface distribution by spectral mixture analysis. *Journal of Remote Sensing of Environment* 84 (4), 493–505. [http://dx.doi.org/10.1016/S0034-4257\(02\)00136-0](http://dx.doi.org/10.1016/S0034-4257(02)00136-0).
- Xian, G., Crane, M., McMahon, C., 2008. Quantifying multi-temporal urban development characteristics in las vegas from landsat and aster data. *American Society for Photogrammetric Engineering & Remote Sensing* 4 (9), 473–481. <https://doi.org/10.14358/PERS.74.4.473>.
- Zhou, L., Dickinson, R.E., Tian, Y., Fang, J., Li, Q., Kaufmann, R.K., Tucker, C.J., Myneni, R.B., 2004. Evidence for a significant urbanization effect on climate in China. *Proc. Natl. Acad. Sci. Unit. States Am.* 101 (26), 9540–9544. <http://dx.doi.org/10.1073/pnas.0400357101>.